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DAYLIGHTING DESIGN FOR THE PACIFIC MUSEUM OF FLIGHT: ENERGY IMPACTS

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ABSTRACT

The daylighting performance of the Pacific Museum of Flight in Seattle, WA, has been analyzed using the DOE-2.1C building energy simulation program. The main exhibit areas of this museum are enclosed on three sides by glass walls and the 48,000-ft^2 roof is completely glazed. Because of the large glass areas, a detailed thermal simulation of the building was carried out during its design phase in order to select glazing parameters that would avoid excessive summer solar heat gain, reduce winter heat loss and, at the same time, provide enough natural light to significantly reduce electric lighting loads. Glazing choices considered included conventional glass, heat mirror, and glass with a low-emissivity coating. On/off, stepped and continuous dimming lighting control systems were analyzed. Daylighting was found to be very effective in reducing annual electric lighting load, peak electrical demand, and the overall annual energy consumption.

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INTRODUCTION

Located at the King County Airport in Seattle, the Pacific Museum of Flight (Fig. 1) is home to one of the most extensive aircraft collections in the world. The 143,000-ft^2 museum is dominated by a six-story-high exhibit area that is enclosed by glass walls on three sides and covered by a 48,000-ft^2 glazed roof. The large glass areas and the desire for an energy-efficient design made it necessary to carry out detailed thermal simulations.

Although Red Barn, the original Boeing Company building, is now part of the museum, this study considers only the performance of the new museum building, designated as "Phase Two", as shown in Fig. 2. Besides the exhibit area, the museum also contains a library, a 268-seat auditorium, office and conference space, and supporting maintenance shops. The irregularly-shaped building is 484 ft long, 249-ft wide, and 76-ft high. The lobby, the auditorium, and all public exhibit areas are on the ground floor, which has three levels. The exhibit area covers more than 64,000-ft^2. The library, offices, and meeting rooms are on the upper floor. Maintenance shops are in the basement, at the same level as the lowest part of the main gallery.

The architectural concept for the building was shaped by the need to naturally light the exhibits. This is the primary reason why the main gallery, despite its unfavorable orientation from the point of view of solar exposure, is enclosed in glass behind a three-dimensional steel frame structure. This frame incorporates an elaborate external shading system made of horizontally-mounted steel pipes (Fig. 3).

To break the monotony of extended monochromatic surfaces, the architects specified three different glass types in each of the large glass walls of the main gallery. Glazing is divided vertically by type with darkest glass on top, lighter glass in the middle, and clearest glass at the bottom (Fig. 4).

Although energy efficiency was only one of the major concerns in the design of this building, the success of the architectural concept depended on resolving several critical issues related to energy performance: (1) control of solar gain, especially in the exhibit area; (2) quality of light in the exhibit area; (3) cost of electric lighting for exhibits; (4) heat loss and heat gain through a building skin dominated by glass; and (5) compliance with King County's energy code. These issues were investigated and successfully resolved with the help of computer simulation during the design phase. This report describes the major results of the simulation process, with emphasis on the selection of glazing parameters and the use of daylighting to reduce electric lighting consumption.

METHODOLOGY

Research results indicate that daylighting can save energy and reduce peak electrical demand in buildings (Arumi 1977; Sanchez and Rudoy 1981; Selkowitz *et al.* 1983; Johnson *et al.* 1984 and 1985). Studies have shown that daylighting design must be done carefully since too much solar gain will increase cooling loads, which may offset savings from reduced electric lighting consumption (Arasteh *et al.* 1985; Johnson *et al.* 1986). Parametric studies on hypothetical office modules give guidance on the amount and transmittance of glass that will yield optimal daylighting benefits for different lighting power densities, lighting control strategies, and climates (Johnson *et al.* 1984). However, it is difficult to extrapolate such guidance to buildings, such as the Pacific Museum of Flight,

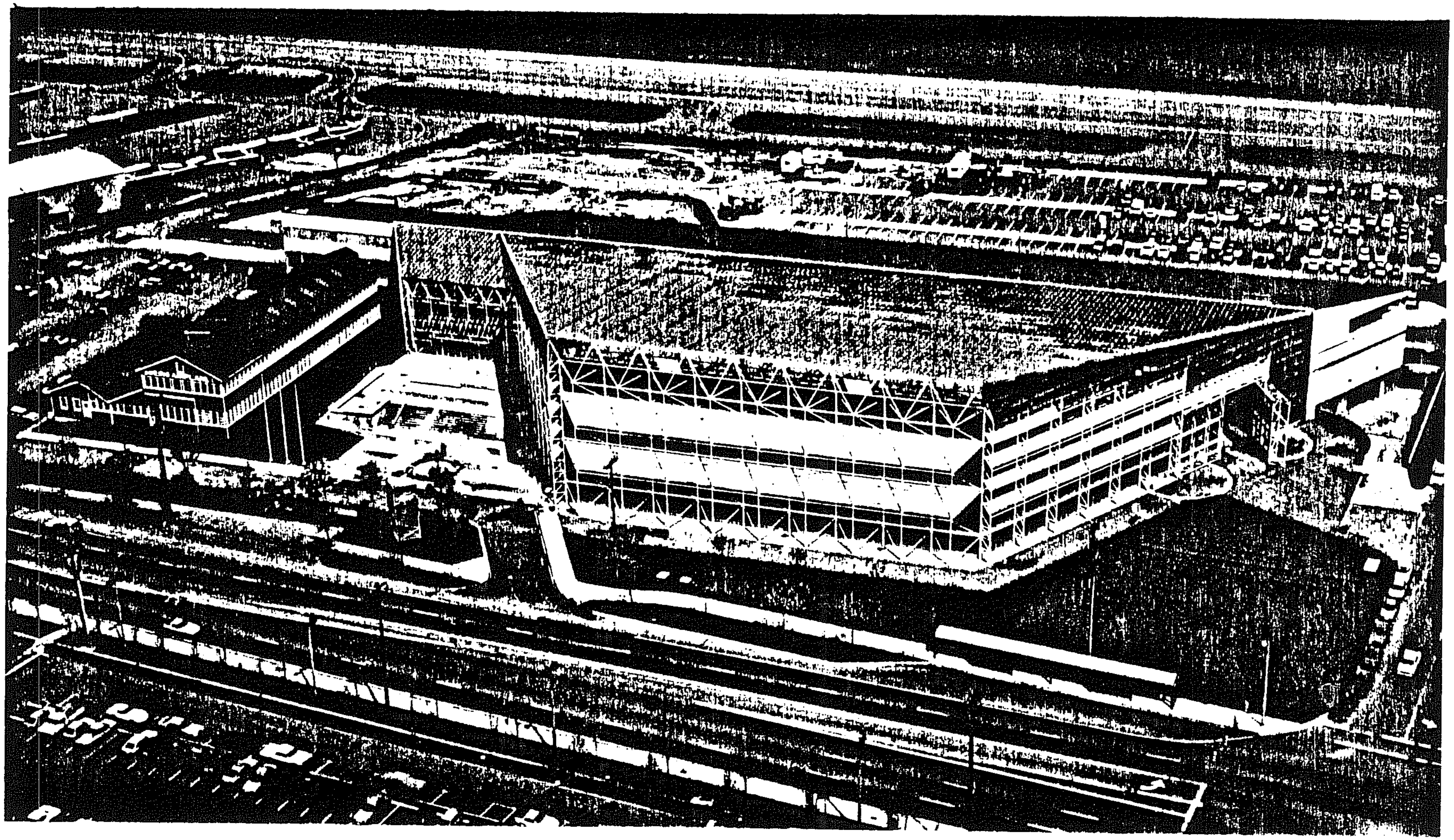

Fig. 1. Aerial view of the Pacific Museum of Flight in Seattle, Washington. The historic Red Barn (left) adjoins the new 64,000-ft^2 steel-and-glass Main Gallery.

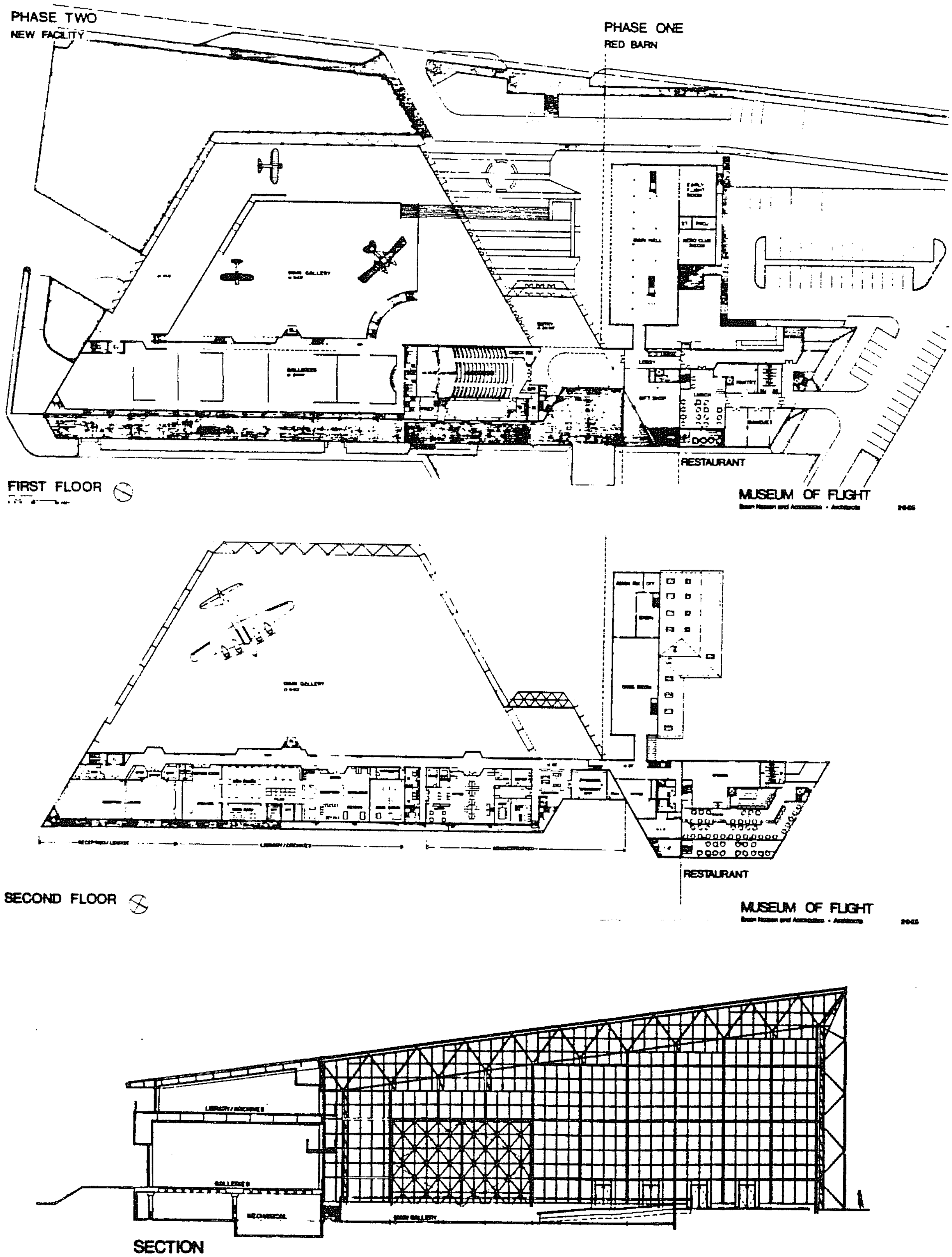

Fig. 2. First and second floor plan and section through the Main Gallery.

which have architectural programs and use patterns that are radically different from those of typical office buildings. For this reason, it was decided that a computer simulation based on a careful, detailed and consistent description of the building's architecture and tailored to the specific characteristics of the museum was required as part of the design process.†

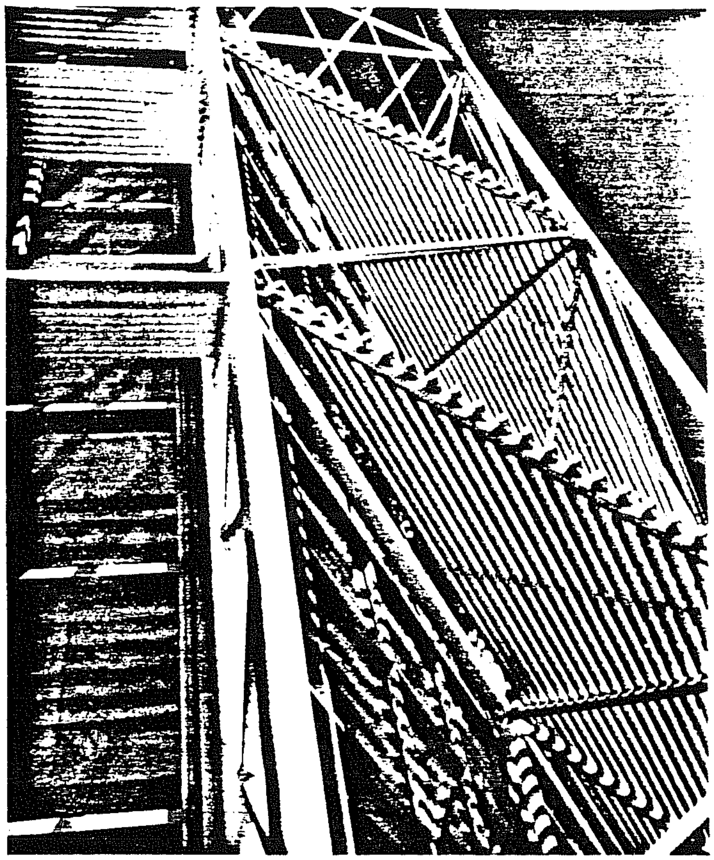

Fig. 3. Detail of the exterior shading system.

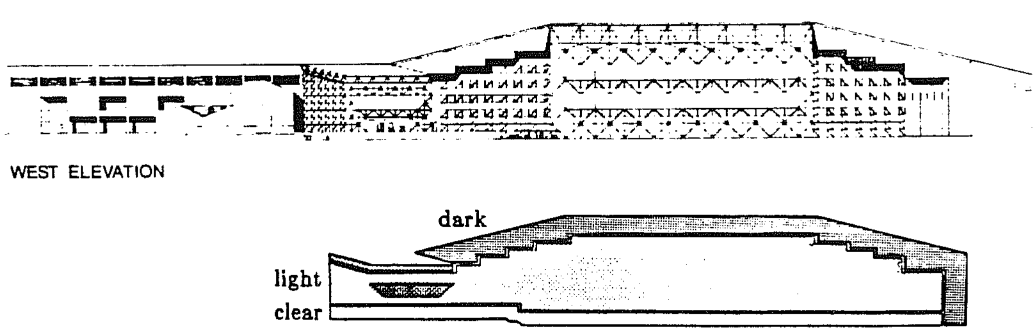

Fig. 4. West elevation showing different glass colors.

† In the conduct of this study, the results of analysis of the energy performance of the Crystal Cathedral (Bazjanac 1980) were only of very limited help. The Crystal Cathedral in Garden Grove, CA, is similar in size and construction type to the Pacific Museum of Flight; however, the Cathedral's microclimate (at the edge of a fog-belt region) and its occupancy restriction to morning and evening hours raise different energy performance issues.

Energy performance and daylighting were simulated with DOE-2.1C, the latest version of the DOE-2 computer program for hour-by-hour building energy analysis (LBL 1984). DOE-2.1C has a new sunspace/atrium simulation feature that allows accurate modeling of spaces which have large amounts of glazing — such as the main museum gallery — and for which heat transfer to surrounding spaces is important. Effects which are accounted for by the sunspace/atrium model include penetration of solar radiation through interior glazing and open doorways between the main gallery and adjoining rooms; convection through open doorways; delayed conduction through heavy interior walls, including the effect of solar radiation absorbed on the gallery side of the walls; and conduction through interior glazing. This report focuses on (a) the effect of the use of different glazing types in the large glass walls and glass roof of the main gallery and the lobby, (b) the effect of the variation of glazing type in the same wall, and (c) the effect of different logic for automatic lighting control systems. The size of the glazed areas is not a variable in itself, as it is predetermined by the architectural concept of the building.

The DOE-2.1C daylighting program (LBL 1984; Winkelmann and Selkowitz 1985) calculates interior daylight illuminance levels and simulates stepped and dimming lighting control systems. Among the factors accounted for by the illuminance calculation are the glazing characteristics (area, orientation, transmittance); the hourly-varying availability of daylight from sun, sky and ground; and the reduction of daylight penetration due to exterior building shades. The program also accounts for the variation of transmittance with angle of incidence for the different glazing types examined in this analysis.

Descriptions of alternative glazings and logic for the automatic lighting control system were changed one at a time for parametric simulation. The simulation results were compared and evaluated; eventually, the generated information and understanding of performance of alternatives were transformed into design recommendations.

The very open character of the building, its non-rectangular form, elaborate external shading, and unusual schedules of use make the DOE-2 description of the building fairly complex (Bazjanac 1985). The description contains 27 thermal zones, nine VAV systems, and a central plant consisting of an electric hot-water boiler, a centrifugal chiller, and a cooling tower. Eight thermal zones are daylit, and 24 are conditioned. Some part of the building will be in use virtually every day of the year. The description of operating conditions (occupancy, use of electric lighting, user-operated equipment, infiltration, thermostat settings and operation of fans) consists of 45 different annual schedules, 21 of which describe the operation of HVAC systems.

Table 1 shows the properties of glazing used in the simulations. Glazings in this set were chosen because of the architects' preference for their light transmission properties and color, because of structural requirements resulting from large glass spans, and because of cost and availability considerations.

TABLE 1

Glass Types Used in Simulation

Glass Type	Number of glass panes	Visible trans-mittance	Solar trans-mittance	Shading coefficient[a]	Conductance[b] (Btu/ft^2-h-F)
Conventional Clear[c]	2	.80	.75	.82	.43
Conventional Green[c]	2	.67	.53	.55	.43
Conventional Bronze[c]	2	.47	.29	.57	.43
Heat mirror Clear88	2	.69	.45	.66	.31
Heat mirror Clear66	2	.54	.31	.48	.30
Heat mirror Clear55	2	.47	.27	.41	.27
Heat mirror Gray55	2	.22	.13	.26	.30
Low-e clear	2	.74	.53	.71	.29
Low-e green	2	.64	.35	.47	.29
Low-e bronze	2	.43	.29	.49	.29
Reflective Triple Glazing	3	.25	.08	.23	.22
Opaque Triple Glazing	3	.00	.00	–	.22

a Shading coefficients listed here represent only nominal values; in the simulations glazing properties are defined through visible and solar transmittance, and the assembly's heat conductance.

b Heat conductance of the total glazing assembly (window) for a 7.5 mph windspeed.

c Representative of that type of commercially available glazing.

DISCUSSION

Wall Glazing

The wall glazing options that were analyzed are summarized in Table 2. Three basic glazing alternatives were compared:

- conventional glass,
- heat mirror†,
- glass with a low-emissivity (low-E) coating.

These alternatives were chosen to satisfy architectural color constraints and the requirement that exhibits be easily viewable from outside the building.

TABLE 2

Wall Glazing Options

Wall sector	Percent of wall area	No. of glass panes	Option: Conventional	Option: Heat Mirror	Option: Low-e
Top	25%	2	bronze	Gray55	bronze
Middle	50%	2	green	Clear55	green
Bottom	25%	2	clear	Clear66	clear

† We use the generic term "heat mirror" to describe an insulating glazing construction consisting of a low-emissivity plastic film suspended between panes of conventional glass. Capitalized, "Heat Mirror" is a registered trademark for the low-emissivity film itself.

Each glazing scheme contains three color variations for the glass. The top sector comprises 25% of the glass surface in all large, multichromatic glass walls. The middle sector contains 50%, and the bottom the remaining 25% of the glass area. Glass in the conventional glazing scheme is double-pane, with bronze on top, green in the middle, and clear at the bottom. The heat mirror scheme is double pane, with Gray55† on top, Clear55 in the middle and Clear66 at the bottom. The low-E glass option is double pane with bronze on top, green in the middle, and clear at the bottom. No single-pane glazings were considered because of their high thermal conductivity.

The simulations show that natural light is abundant with each glazing scheme in all daylit spaces. For the whole building, daylighting for the conventional glazing scheme reduces annual electric lighting consumption by 47%. With heat mirror the reduction is 46% and with low-E glass it is 47%.

The performance of each of the glazing schemes can also be measured in terms of the effect on annual heating and cooling loads. As shown in Fig. 5, conventional glazing causes the highest heating and cooling loads because of comparatively high solar transmittance and thermal conductance. However, the high

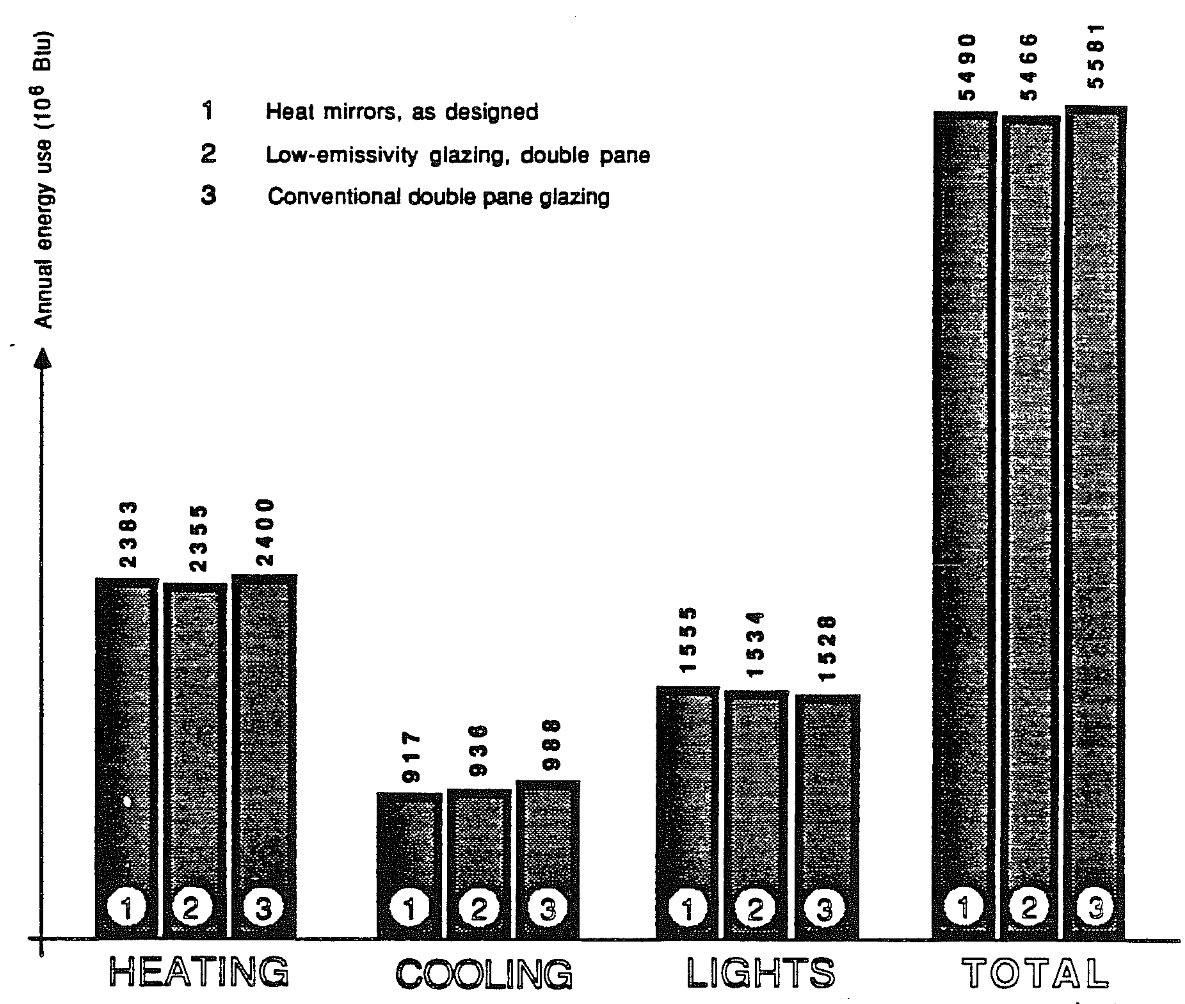

Fig. 5. Building annual site energy use for different exterior wall glass types.

† The color (Gray or Clear) indicates the color of glass in the heat mirror assembly. The number (55 or 66) indicates the percent visible transmittance of the low-E film.

visible transmittance for this option gives the highest daylight levels, resulting in the lowest electric lighting load. Heat mirror causes the lowest annual cooling load for the building: 917 million Btu (MBtu). Low-E glazing causes the lowest annual heating load: 2355 MBtu, which is 28 MBtu less than with heat mirror.

Figure 5 shows that the building design is not very sensitive to the type of glass used in the walls. Overall, the annual site energy consumption per square foot of gross floor area is 38,500 Btu/ft^2-yr with heat mirror vs 38,300 Btu/ft^2-yr with low-E glass. Despite its slightly higher energy consumption, heat mirror glass was selected over low-emissivity, because in the largest (middle) sector of the multichromatic glass schemes, heat mirror Clear55 has a significantly lower solar transmissivity than the corresponding green low-E glass, particularly in the UV portion of the solar spectrum. The minimal difference in natural lighting (1% in favor of low-E glass) was judged to be insufficient to offset the benefits from lower exposure of exhibits to UV rays.

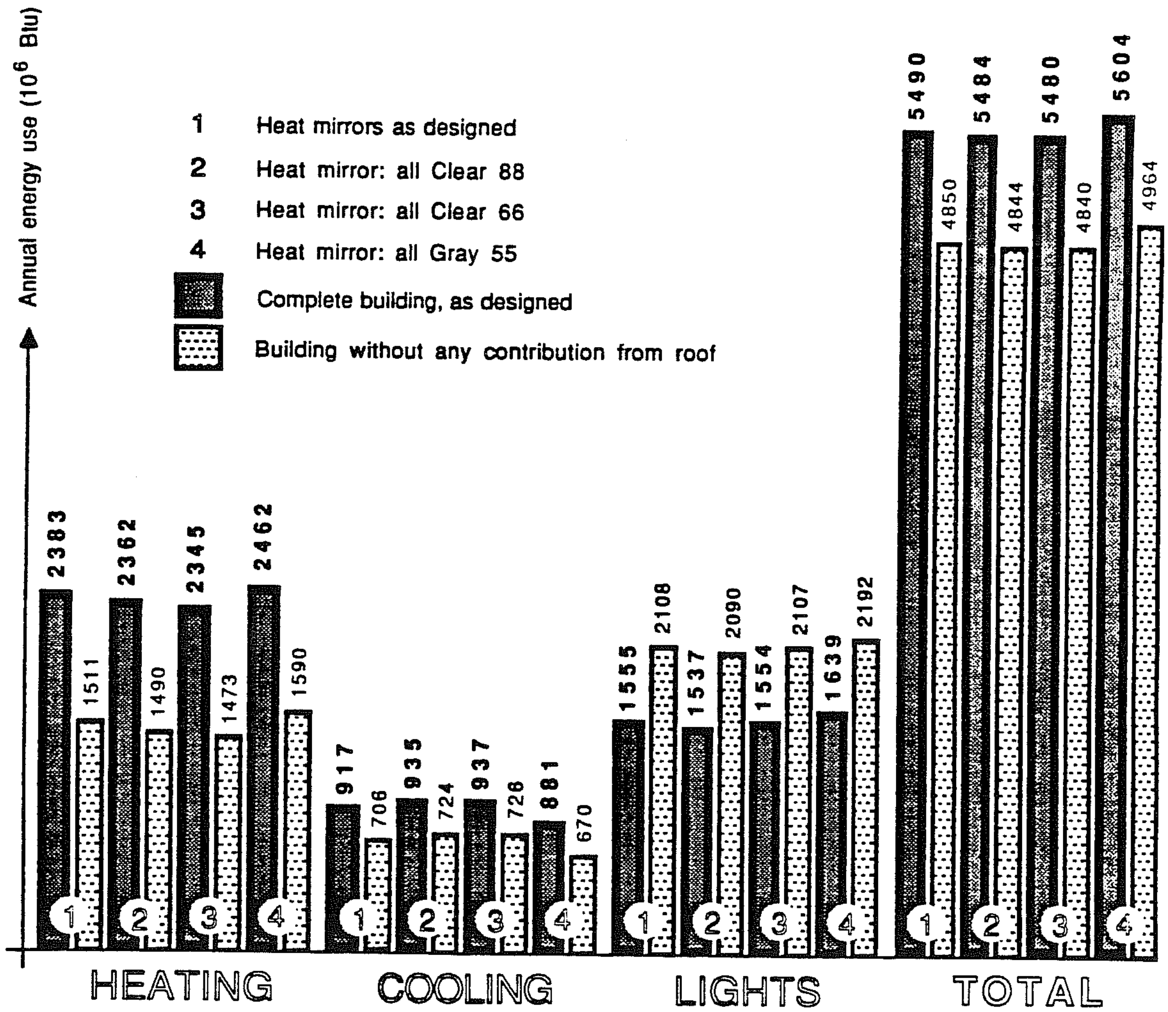

Fig. 6. Building annual site energy use for different exterior wall heat mirror options.

Figure 6 shows a comparison of performance of different heat mirror. For this comparison, all exterior glass walls in the simulation are monochromatic (i.e., there is no vertical differentiation of glass type in any large glass walls). Heat mirror Gray55 causes the lowest cooling load, but it also causes the highest heating and electric lighting load. Heat mirror Clear88 and Clear66 yield virtually identical overall annual building energy consumption: 38,400 Btu/ft^2-yr. Again, heat mirror Clear66 is preferable since it allows less UV to reach the exhibits.

The apparent minimal difference in performance of alternative wall glazings is somewhat deceiving because the walls are well shaded externally and because the glass roof and the part of the building which is not glazed account for a large portion of loads. Figure 6 shows that when the contribution of the roof is excluded (i.e., when roof conductive heat transfer and solar gain are eliminated), the difference between wall glazings becomes more significant.

Roof Glazing

The architectural concept called for a monochromatic treatment of glass in the roof. Three major choices were considered: heat mirror Clear55, triple glazing with reflective coating, and opaque glazing. Heat mirror represents a choice in which the sky can be seen almost clearly from inside the main gallery and lobby at all times. The sky can be seen with varying clarity through triple glazing with

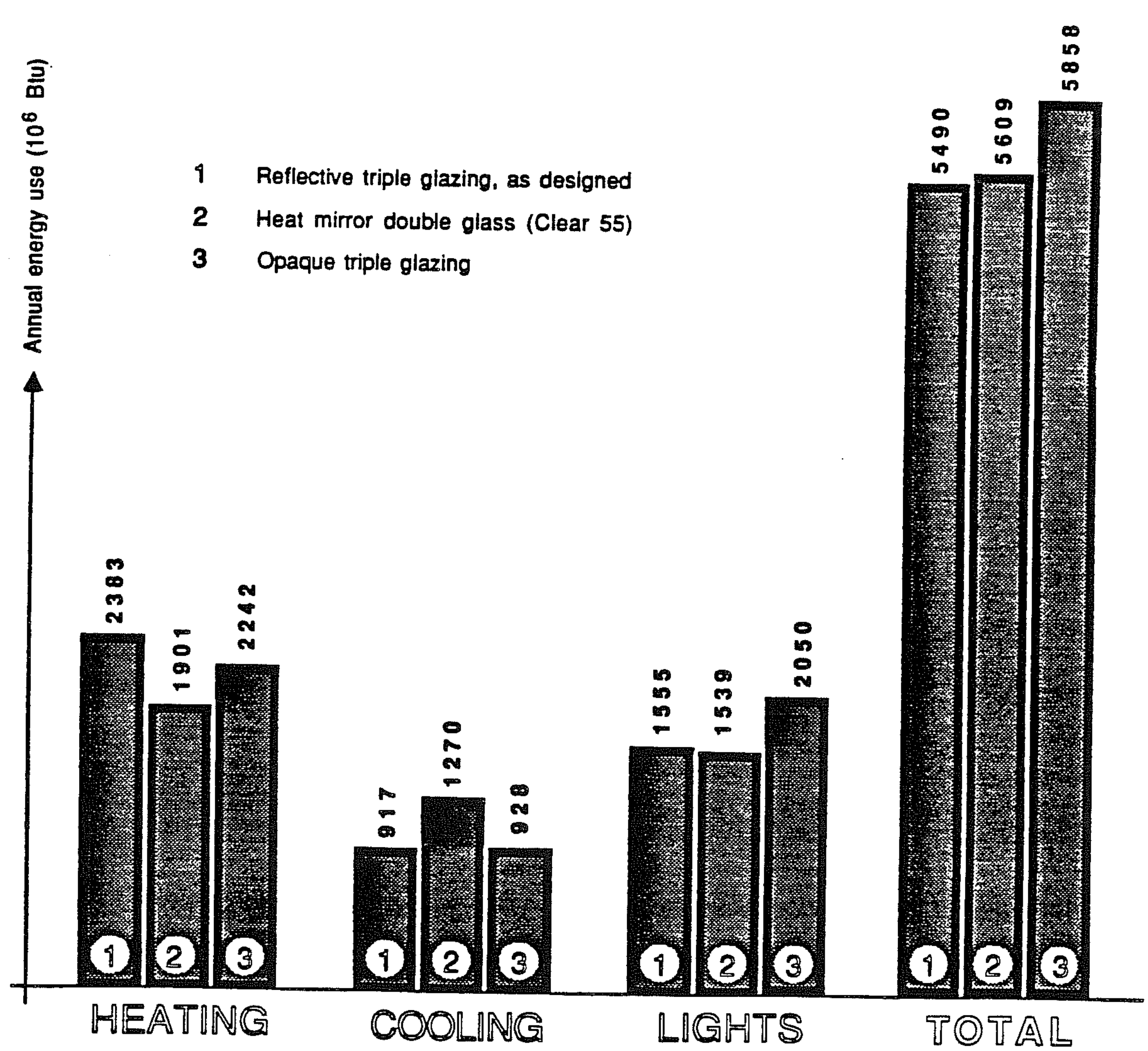

Fig. 7. Building annual site energy use for different roof glazing options.

reflective coating, the clarity depending on the reflectivity of the coating, outside illuminance and the position of the sun. Opaque glazing prevents any view of the sky from the inside, but it still retains the appearance of glass from the outside. Unlike the large glass walls, the glass roof is on the outside of the three-dimensional steel frame structure and is not shaded.

Figure 7 shows the effect of roof glazing choice on the building energy consumption. Heat mirror Clear55 causes the lowest heating and the highest cooling load. Reflective triple glazing causes the opposite: the highest heating and the lowest cooling load. Opaque triple glazing creates a severe daylighting penalty, as the electric lighting load increases by 32% relative to the load from reflective triple glazing. With regard to natural lighting, heat mirror in the roof is only marginally better than reflective triple glazing.

The final choice for the roof was reflective triple glazing. It was recommended because it results in building energy consumption which is 800 Btu/ft^2-yr lower than with heat mirror, and because it incorporates tempered (top pane) and laminated safety glass (bottom pane) required by the Uniform Building Code. Heat mirror was eventually eliminated from consideration since it was believed that large, horizontal sections of heat mirror film would, over time, deflect in the middle, causing surface stresses and associated degradation of the low-E coating. This belief was later shown to be incorrect based on experience in several buildings with horizontal skylights and atria ceilings in which the heat mirror film showed no evidence of deformation.

Automatic Lighting Control System

Most of the public exhibit viewing time is during sun-up hours. With abundant natural light available inside the building, the effectiveness of the use of daylighting depends primarily on the performance of the lighting control system. Four different control systems are compared in Fig. 8: simple on/off, stepped with three steps, stepped with ten steps, and continuous dimming. The role of these systems is to sense illumination in daylit spaces and automatically supplement natural with electric light when necessary to maintain illumination at a design level of 50 fc. For stepped systems, the number of steps is linearly distributed between full power (2.35 W/ft^2) and zero. The continuous system dims linearly from 100% power consumption at 100% light output to 10% power consumption at zero light output.

The continuous dimming system is the least effective. The continuous, precise supplementing of natural light is offset by this system's consumption of power even when no electric lighting is needed. Even the simple on/off system, which is less expensive, is less energy-consuming: even though it is at full power whenever illumination from natural light in daylit spaces drops below design level, it consumes no power at all when that level is met by natural light alone. Conversely, the 10-step linear system (which also consumes no power when not supplying electric light) is most effective and yields the lowest electric consumption from lighting, although the 10 steps do not match the demand for electric lighting as closely as continuous dimming. This situation does not change even if visible transmittance of all glass is reduced by 50% in the simulation. It was decided to install a three-step system (Linn 1987) as an affordable alternative to the 10-step system.

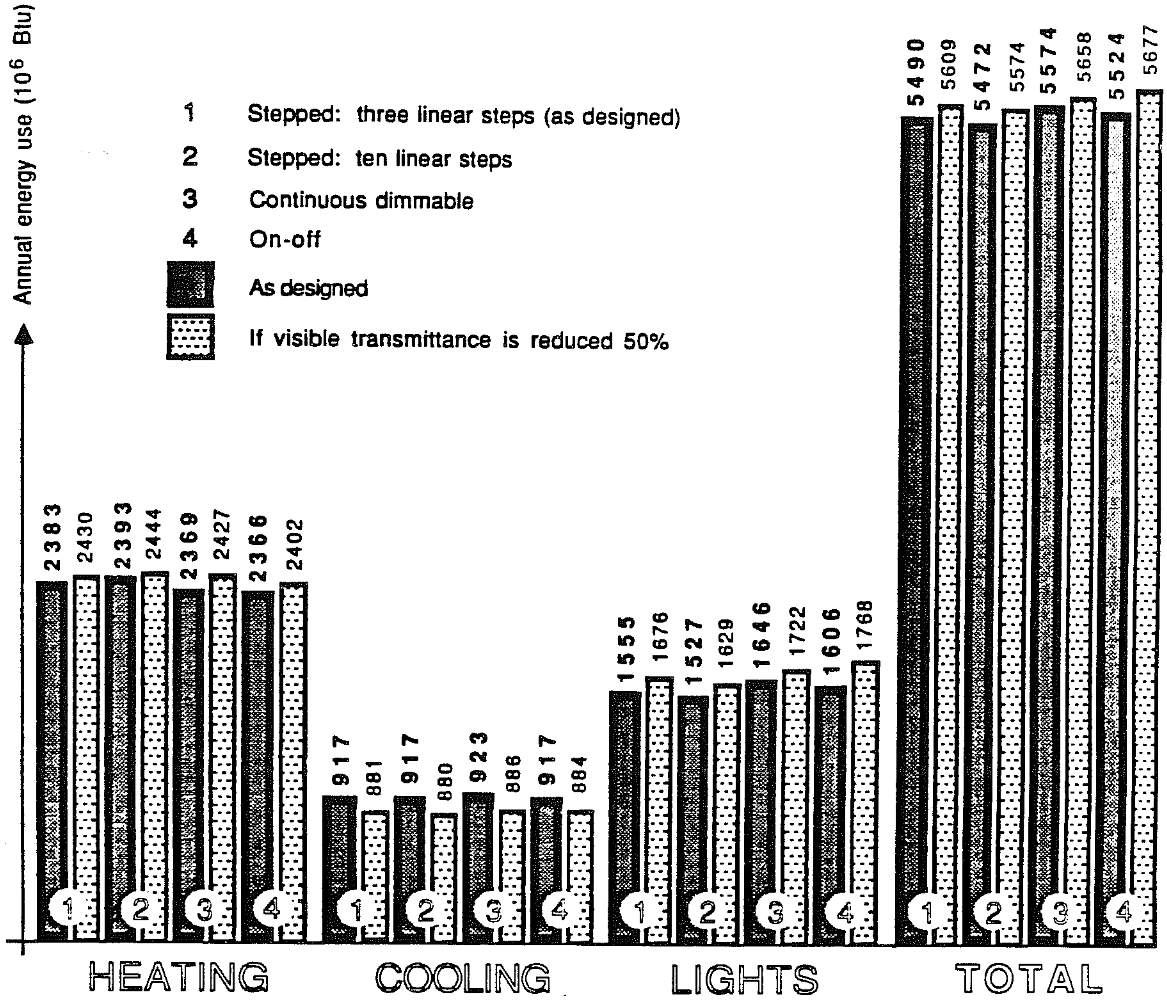

Fig. 8. Effect of automatic lighting control systems on building annual site energy use.

Daylighting Performance

There is a high potential for daylighting in the museum since 77% of the annual electric lighting load (without daylighting) comes from spaces which can be daylit. The DOE-2 simulation predicts that the annual electric lighting load in spaces with large, multichromatic glass walls (main gallery and lobby) will decrease 78% with daylighting. About 80% of all exhibit areas is so well daylit that no electric lighting at all is required during sun-up hours of use from April through August, and very little the rest of the year. The reduction of the annual lighting load in other daylit spaces, including offices and meeting rooms, varies from 24% in the auditorium lobby to 43% in the library.

The predicted lighting energy reduction for the building as a whole for different months of the year and for different hours of day is shown in Table 3. On a monthly basis, the lighting energy reduction varies from 32% in December, when days are short and overcast, to 52-54% in the summer, when days are long, sun angles are high, and skies are clearest; the overall annual reduction is 46%.

TABLE 3

Percent Lighting Energy Reduction by Daylighting for the Entire Building

Month	Hour of day 4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	All hours
January	0	0	0	0	0	20	25	55	57	62	57	53	48	19	0	0	0	0	35
February	0	0	0	0	16	28	30	59	59	63	59	58	57	48	4	0	0	0	42
March	0	0	0	12	47	36	36	60	60	66	61	60	58	55	57	0	0	0	48
April	0	0	9	56	44	23	39	61	63	66	62	61	59	60	66	32	0	0	50
May	0	0	53	60	26	24	62	63	68	63	63	63	62	69	60	56	4	0	53
June	0	3	50	60	24	23	61	62	67	62	62	62	61	70	60	57	32	0	52
July	0	0	55	61	28	26	63	63	68	63	63	63	63	70	61	58	30	0	54
August	0	0	16	59	24	24	62	62	67	62	62	62	62	69	59	41	0	0	52
September	0	0	0	40	22	22	60	61	67	62	62	61	60	68	48	5	0	0	50
October	0	0	0	2	30	30	58	60	64	60	60	58	55	47	3	0	0	0	46
November	0	0	0	0	12	31	32	57	58	63	57	54	46	6	0	0	0	0	35
December	0	0	0	0	0	19	27	55	57	60	54	50	42	0	0	0	0	0	32
Annual	0	0	15	29	25	26	52	60	63	63	60	59	56	47	24	21	6	0	46

The effectiveness of daylighting is best demonstrated in the comparison of the building's annual energy performance with and without daylighting shown in Table 4. In the case with daylighting, the three-step lighting control system operates electric lights only when needed to supplement natural light, or when no daylight is available. Without daylighting, electric lights are turned on at all times in the particular area of the building which is in use, regardless of the availability of natural light. With daylighting, the building consumes 386,000 kWh per year less on electric lighting than without daylighting. This represents a 17% annual savings in the building's overall energy consumption.

TABLE 4

Effect of Daylighting on the Components of Building Energy Consumption

	Without daylighting			With daylighting		
	(10^6Btu)	(10^3kWh)	(fraction)	(10^6Btu)	(10^3kWh)	(fraction)
Space heating	2079	614	32%	2383	698	43%
Space cooling	983	288	15%	917	269	17%
Fans and HVAC auxiliary	519	152	8%	491	144	9%
Lights	2872	842	43%	1555	456	28%
Miscellaneous Equipment	144	42	2%	144	42	3%
Total	6615	1938	100%	5490	1609	100%

The benefits from daylighting are also evident in the peak electrical demand which the museum generates (Table 5). Daylighting reduces the building's monthly peak electrical demand by a minimum of less than 10% in the winter and a maximum of 30% in the spring. During the critical summer months (June - September) the peak demand is reduced by at least 22%. The average annual reduction is 14%. The time of peak demand during the winter (November-February) shifts from 11 A.M. without daylighting to 5 P.M. with daylighting. The reason for this is the rapid decrease in late-afternoon daylight which causes the electric lights to come fully on after about 4 P.M. (see Table 3).

TABLE 5

Effect of Daylighting on Peak Electrical Demand

	Peak Electrical Demand (kW)				Reduction
Month	(Day/hr)	W/O Daylighting	(Day/hr)	W/Daylighting	Due to Daylighting
January	(26/11 A.M.)	880	(5/4 P.M.)	879	0.1%
February	(9/11 A.M.)	880	(2/5 P.M.)	804	8.6%
March	(9/11 A.M.)	871	(10/11 A.M.)	749	14.1%
April	(15/11 A.M.)	674	(15/10 A.M.)	638	5.4%
May	(4/5 P.M.)	520	(21/5 P.M.)	363	30.3%
June	(16/4 P.M.)	716	(16/4 P.M.)	557	22.1%
July	(23/5 P.M.)	708	(23/5 P.M.)	545	23.0%
August	(10/5 P.M.)	709	(10/5 P.M.)	544	23.2%
September	(5/5 P.M.)	630	(5/5 P.M.)	456	27.7%
October	(28/11 A.M.)	636	(28/11 A.M.)	557	12.4%
November	(26/11 A.M.)	870	(23/5 P.M.)	801	7.9%
December	(29/11 A.M.)	880	(29/5 P.M.)	834	5.2%
Annual average		748		644	13.9%

Daylight Saturation and Glare

DOE-2 simulation shows that the daylight illuminance in the main gallery and lobby significantly exceeds the design illuminance setpoint for most of the occupied hours. This "daylight saturation" is necessary to minimize energy consumption, as electric lighting in these spaces comprises the largest block of energy consumption in the building. The architectural constraints (other than energy efficiency) in the selection of glazing, made daylight saturation unavoidable. As is evident from Fig. 9, even a 50% reduction in visible transmittance of all glass (without changing the shading coefficient) would cause only a minimal increase in electrical lighting and overall building loads. Only reduction of well over 50% in visible transmittance would begin to eliminate daylight saturation. However, glass with such low transmittance would make exhibits invisible from the outside.

Abundance of natural light inside the building raises concerns about glare. Glare could not be properly studied during the design of the building because the dense three-dimensional structural frame which supports the glazed roof from the inside (Fig. 10) and the glass walls from the outside (Fig. 1) cannot be modeled

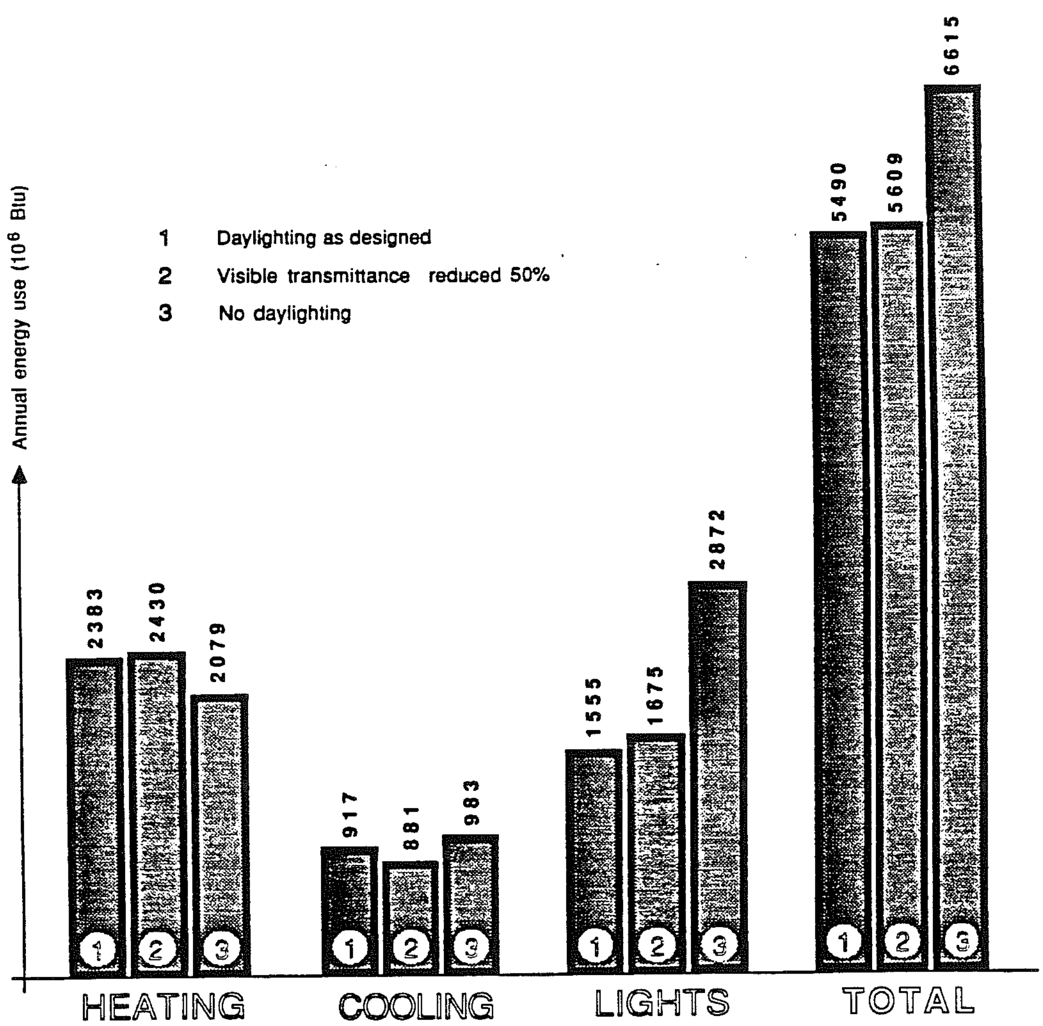

Fig. 9. Effect of daylighting on building annual site energy use.

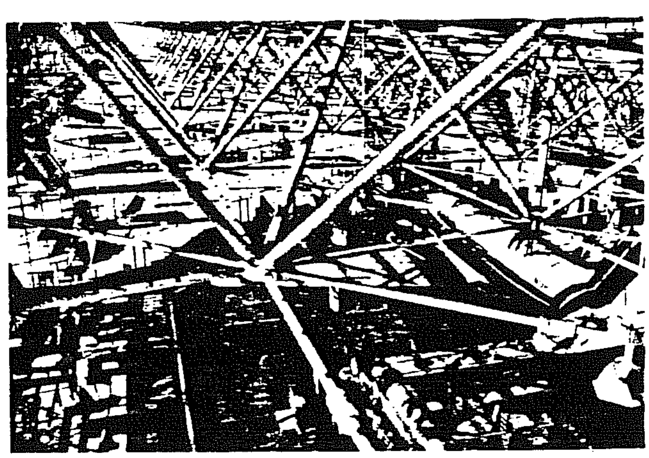

Fig. 10. Interior view of Main Gallery showing roof support structure.

for meaningful glare studies with DOE-2. Photometric tests with physical models were not possible because of prohibitive costs (Stix 1988). Since no glare problems exist in the Crystal Cathedral (Bazjanac 1980), a building with a very similar structural frame and interior daylight environment, it was assumed there would be no significant glare in the Pacific Museum of Flight. This assumption has since been proven correct.

Compliance with Energy Code

The building did not meet the prescriptive King County energy code (King County 1980) because of the amount of external glazing. The alternative method of compliance allowed by this code requires the simulated annual energy consumption of the proposed design to meet that of a "standard" design, one which satisfies the prescriptive code. Since the King County code permits only a 20% improvement in *any* load component of the proposed design, this building cannot obtain proper credit for daylighting or for external shading.

The code does not ordinarily define a design energy budget. However, to provide a chance for compliance, King County defined a design energy budget of 60,000 Btu/ft^2-yr specifically for this building. To obtain the building permit the architects had to demonstrate that the overall annual energy consumption of the proposed design did not exceed this value.

The DOE-2 analysis shows that the building meets the standard easily. The total annual predicted site energy consumption is 38,500 Btu/ft^2-yr. As shown in Table 3, 43% of the energy is consumed for heating, 17% for cooling, 9% for fans and other HVAC auxiliaries, 28% for electric lighting (including security lighting), and 3% for user-operated equipment.

CONCLUSIONS

Careful architectural, mechanical, and electrical design coupled with computer analysis have resulted in a building that is expected to be energy efficient and, at the same time, is low in first cost. The actual construction cost was \$112/ft^2 compared to a typical cost of \$250/ft^2 which can be expected for large museums.

We have shown that daylighting is a particularly effective energy conservation strategy for the new Pacific Museum of Flight. The large energy saving from daylighting is possible because:

1. Large glazed areas of relatively high visible transmittance produce abundant natural light in the exhibit spaces during most hours of use.

2. Electric lighting is controlled automatically by a stepped system with sensors. The system delivers only as much electric light as necessary, and consumes no power when not supplying light.

3. The glazing has a relatively low solar transmissivity. This helps control the cooling load.

4. The glazing has moderately low conductance, which prevents excessive conductive heat-loss and heat-gain through glass surfaces.

Despite its large glazing area, the building is actually less sensitive to glazing type than might be expected. This is primarily due to the very effective exterior shading of the vertical glazed areas of the main gallery. Relative to external glazing selected for the building, the differences in annual energy use for the studied alternative glazing schemes vary from a decrease of 0.5% to an increase of 2.1%.

The energy premium paid for honoring the architectural concept for the glazing is minimal. The building is expected to consume only 100 Btu/ft^2-yr more than the best energy-performing glazing scheme investigated in this study.

The Pacific Museum of Flight opened in July 1987. As one of the conditions for issuing the building permit, the King County Building Department stipulated a post-occupancy energy study. The study will include the monitoring of actual building use patterns, illumination in daylit spaces, and the building's energy consumption. These measured results will provide the information necessary to judge how well the predicted benefits from daylighting, as simulated during the design of the building, are met in reality.

ACKNOWLEDGEMENTS

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FIELD MEASUREMENTS OF LIGHT SHELF PERFORMANCE IN A MAJOR OFFICE INSTALLATION

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ABSTRACT

Electric lighting is a major component of electrical energy use in large commercial buildings and has additional significant impact on the cooling energy requirements. This paper evaluates the monitored performance of such an integrated lighting scheme in a recently completed 600,000-ft2 office structure located in the San Francisco Bay Area. Decentralized data acquisition systems monitored 62 different locations in the building between May 1985 and January 1986, recording average illuminance levels and corresponding ambient lighting power usage across the north and south building sections. A graphic summary of data compares the performance of effectiveness of the building's lightshelf system for north and south orientations. One counterintuitive conclusion of the study is that the "dimmer" north side light shelf scheme exhibits a higher potential (69% reduction from full power) for electric light reduction than the "brighter" south side scheme (56% reduction).

1. INTRODUCTION

Electric lighting consumes 30% to 50% of the electrical energy used in large commercial buildings and has additional significant impact on the cooling energy requirements. The use of daylight for ambient illumination can substantially reduce this energy usage. However, along with these important benefits come potential penalties for daylighting designs whose actual performance is considerably different than the original design goals. A daylighting design that lags far behind the original targeted illumination levels may not achieve the projected electric light energy savings and associated peak load reductions. A design that consistently provides too much daylight, on the other hand, can be a liability due to increased solar heat gain and discomfort to occupants from glare and thermal gradients. The challenge of good daylighting design is to produce a solution that delivers the needed illuminance levels to the work spaces while avoiding the extremes of performance that generate these liabilities.

Over the last decade, an increasing emphasis on daylighting has fostered the development and use of new tools to predict the performance of daylighting schemes. The impressive progress of these new computer programs, nomographs and modeling techniques is marred only by the lack of documented examples of the performance of existing daylighted buildings that could validate their predictions. The expense, inconvenience and expertise necessary to instrument and analyze an existing building have retarded the generation of a body of documented case studies from which to learn.

In 1985, Lawrence Berkeley Laboratory (LBL), with support from Pacific Gas and Electric Company, performed an extensive analysis of a recently completed daylighted office building in the San Francisco Bay Area. This innovative structure represents a major investment in daylighting by a large U.S. corporation seeking reduced energy consumption, lower peak electrical demand and improved employee productivity. The initial design was strongly driven by daylighting considerations with decisions based on thorough analysis using the best energy and illuminance design tools available at the time. The DOE 2 energy simulation program was applied to evaluate energy consumption patterns in the original building proposal. To this technique was added analysis based on scale models, first with a small mass/shading model, then with larger-scale daylighting models tested in LBL's Sky Simulation Facility. The resulting structure was one in which daylighting-related concerns played a major role.

The product of this design process is a five-story, 600,000-ft2 office building occupied by 3000 technical personnel in open-plan offices. As shown in Figure 1, the rectilinear mass of the building is elongated along an east/west axis producing major fenestration surfaces facing roughly north and south. (The building actually faces approximately 25 degrees west of south.) Building functions lacking a strong relationship to daylighting are grouped into two explicit core units, designed with opaque surfaces and placed on the east and west ends of the building to prevent the adverse radiation aspects associated with these orientations. A central atrium provides light, visual interest, circulation and drama to the building's interior spaces.

An important strategy in the building's design is an explicit separation of systems providing task and ambient illumination. Ambient illumination is provided by daylighting backed-up by indirect fluorescent lighting when needed. Task lighting is provided by individually controlled fixtures built into each workstation. The building design pushed the limits of experimental daylighting techniques to provide ambient daylighting across the full 90-ft width from exterior wall to atrium edge. To accomplish this the exterior walls are fully

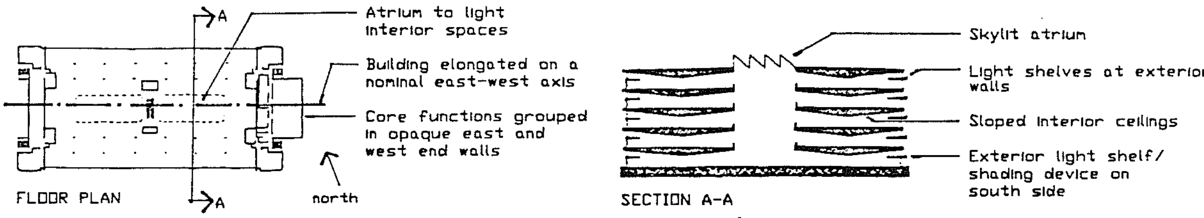


Figure 1. Diagram of building showing daylighting features.

glazed and have an exaggerated floor-to-ceiling height of 15 ft. The building also incorporates ceilings that slope from 15 ft at the atrium and exterior walls to 9 ft at the central corridor. This slope is designed to intercept and reflect illuminance from large light shelves located along both north and south exterior walls. These horizontal interior light shelves are about 7 ft 6 in above the floor and extend inward 12 ft 2 in from the exterior glazing. As indicated in Figure 2, the light shelves create a division between vision glazing below and clear glazing to admit daylight above the light shelf surface. To reduce glare and winter heat gain, the vision glazing has relatively low transmittance. The south side of the building has an exterior light shelf extending 4 ft out from the exterior wall providing additional light collecting area and shading the vision glass below. The central atrium brings additional light to the interior of the building. The entire roof area of the atrium is glazed in a four-bay sawtooth configuration featuring high-transmittance translucent glazing in the sloped planes.

A target ambient illumination level of 350 lux was established for circulation and casual tasks. This illumination is provided by daylight whenever possible and supplemented by indirect fluorescent ceiling fixtures when necessary. The fluorescent fixtures automatically respond to available daylight with a continuously dimming photosensor-controlled system. This system is capable of dimming the fluorescent lights to 24% of full power (representing 20% of full light output) in response to available daylight. Additionally, a separate computer-based control system turns the lights off during scheduled periods of low occupancy. The LBL investigation examined both the ability of the daylighting architectural features to provide the targeted illuminance levels and the response of the automatic dimming system to the daylight provided. Separate papers have reported the performance of the electric light dimming system and its related energy savings. [1,2] This paper discusses the performance of the architectural daylighting features with an emphasis on the relative effectiveness of the light shelf system for north and south orientations. This is of particular interest because most studies of light shelf performance [3,4,5] have provided mixed conclusions regarding their effectiveness. This building utilizes light shelves on a scale much larger than previously attempted.

2. NORTH AND SOUTH BUILDING SECTIONS

The design of any daylighting scheme is complicated by the fact that the four cardinal orientations have very different solar performance characteristics, and this variation must be accommodated within an integrated architectural response. In the building studied, the design solution limited major glazing to only two facades, the north and the south, reducing the complexity of this challenge. The resulting design uses a single strong architectural vocabulary of linear horizontal light shelves running the full 400-ft length of the building on both the north and south sides. The design thus represents a flexible solution with a geometry capable (with minor modifications) of accepting both the beam-dominated daylighting of the southern exposure and the diffuse-sky conditions of the north. An interesting aspect of this study was to evaluate the dramatically different light qualities this scheme produces for the two orientations.

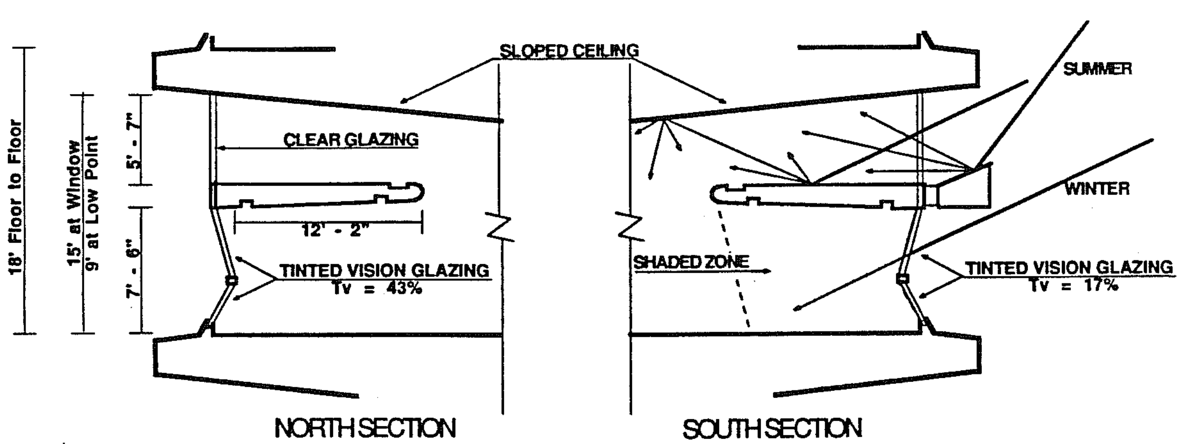


Figure 2. Schematic section through south-side and north-side light shelves.

Schematic sections of the north and south exterior walls are provided in Figure 2. (In this paper, we shall refer to the 45-ft section of the building from the exterior wall to the center-line corridor as the "exterior zone" and the 45-ft section from the atrium edge to the center-line corridor as the "atrium zone".) The south side design is strongly influenced by beam sunlight. Its additional exterior light shelf serves three functions in controlling this intense direct light: its upper white angled surface reflects high summer beam sunlight far into the building's interior; it screens direct view of the sky vault to reduce glare; and it shades the view glazing from sun during the summer. In fact, its geometry is such that the view glazing is fully shaded from direct-beam sunlight in the summer, causing the adjacent area to be darker in the summer than in other seasons. To reduce glare and winter heat gain, the vision glazing below the south light shelf has a relatively low transmittance of only 17%.

Since the building faces about 25 degrees west of true south, the north exterior zone receives a sharp burst of early-morning direct-beam sunlight. The rest of the day, however, it gets only diffuse northern light, giving it an entirely different daylighting character. The north sky provides softer light into this zone, which has higher-transmittance view glazing (43%) and no exterior reflector. The absence of the exterior reflector shading the view glazing in summer months causes this region to be brightest during the summer season.

Both the north and south sections are open to the atrium from about 2.5 ft above the floor to the full 15-ft ceiling height. The office areas adjacent to this open span gain their primary natural light from the atrium's glazing high above. This provides natural lighting with a strong downward component. Although the original design proposal called for smaller light shelves lining these atrium openings to redirect the light deeper into the interior, these were eliminated due to budget constraints.

3. QUALITATIVE IMPRESSIONS

Our measurement program was begun with a series of preliminary site visits. A visual inspection of the building, supplemented with snapshot measurements using hand-held instruments, provided early insight into the differing characters of these north and south sections. Although the dimly lit entry lobby on the south side was not well developed in the daylighting scheme, one moves quickly past this to the central atrium, which presents a pleasant brightness and serves as a focal point of the building. From escalators rising through the atrium's center there are views in each direction of the surrounding office spaces. The atrium provides a definite dramatic flair to the space and offers welcome relief to an open-office plan of this size. At the same time, due to its extensive glazing the atrium always seems more the location of light than a source of light. Though the offices surrounding the atrium are adequately lit, they seem dim in comparison to the brightness of this center space. Light from the overhead atrium glazing ranges from a strongly diffuse character on the south side of the atrium to slightly directional light on the north side. On both the south and north sides of the atrium illuminance levels drop off rapidly as one moves away from the atrium edge.

Overall, the south-side exterior zone appears quite bright and has a dynamic light quality through the year (an impression confirmed by spot illumination readings exceeding 1500 lux 20 feet from the exterior wall). However, this bright appearance doesn't apply to the area directly under the light shelf and adjacent to the view glazing. This area seems relatively dim, and its low-transmittance view glazing appears dark when compared to the clear glazing above the light shelf. To compound this problem, interior horizontal venetian blinds have been retrofitted to the south-side exterior view glazing. Although they are usually retracted, the blinds are dark in color and their presence at the window head further reduces the transmission of light. In contrast with the view windows, the clear glazing above the light shelf is occasionally a source of glare.

The north-side exterior zone, on the other hand, appears to have a more even distribution of light. This side seems dimmer than the south, and it has neither the extreme high nor low illuminance levels apparent in the south side. Glare is not a problem on the north exterior zone, but can be problematic at the atrium edge. Overall, the north has a less dramatic lighting quality that shows little variation with changes in season or weather conditions.

In their differing characters, the building's two exterior zones are not unlike the tortoise and the hare. The south side is exposed to a more volatile environment with rapid changes in beam radiation. It consequently exhibits periodic excesses in quantity and variability of natural light. The northern side has a much calmer character related to the consistent diffuse light from exterior skies that varies slowly and over a smaller range.

4. QUANTITATIVE EVALUATION

The measurement of an existing, occupied building poses some interesting technical challenges. Instrumentation must be installed with minimal disturbance to the building occupants and with an orderly routing of sensor wiring. Our data-acquisition strategy was based on the deployment of four battery-powered dataloggers to collect readings at 28 sensor locations. Measurement locations were changed at three-week intervals. The use of four Campbell Scientific Model CR-21 dataloggers allowed relatively short analog sensor wiring runs and flexibility in sensor placement. Data were stored on digital cassettes and downloaded in the field to a portable microcomputer for off-site evaluation. Characterization of interior lighting patterns was based on LiCor 210S photometric sensors. Illuminance profiles across both the north and south building sections were obtained from a series of ambient illuminance measurements taken in a horizontal plane at partition height, 5 ft 8 in above the floor. Additional photometric sensors were located in the volume above the interior light shelves. Lighting power demand for individual lighting circuits was monitored by Ohio Semitronic PC5-59C watt transducers in the local electrical closet. A third set of sensors measured representative air and surface temperatures at selected locations.

Data were collected from February 1985 until January 1986. Preliminary site visits with hand-held instrumentation established the third floor as a representative floor. Data were recorded for three-week periods across a horizontal section of the south side of the third floor, then across a similar profile of the north side and finally in a vertical section across all floors along the atrium edge. Data sets were obtained during the summer, equinox and winter. All of the data presented in this paper represent summer conditions and thus should not be extrapolated beyond that season. This paper describes the net performance of the daylighting design which is based on a complex interaction of the optical properties and geometries of the individual daylighting components (light shelves, atrium, sloped ceilings, etc.). Lab measurements, using a scale model of the light shelf in a large integrating sphere, is now in progress to disaggregate the relative importance of each parameter. The results of this work will be reported at a later date.

5. COMPARISON OF NORTH-SIDE AND SOUTH-SIDE DATA

To establish the performance of the daylighting system independent of the electric light dimming system, we have analyzed illuminance data from a series of unoccupied summer days in which there is no electric lighting component. (The absence of electric lighting during these days was confirmed by examining concurrent lighting power consumption data.) These monitored performance data substantiate many of the qualitative observations.

Typical data for interior illuminance under summer clear-sky conditions are shown in Figure 3. The south side of the structure, strongly influenced by beam sunlight, exhibits substantial variation in illuminance throughout the day. Interior illuminance is low during the morning hours but rises quickly as direct sunlight strikes the exterior light shelf. Peak illuminance readings 13 ft from the exterior wall exceed 1200 lux, almost four times the target of 350 lux. Summer represents the darkest season for this area and winter levels can reach well above 2500 lux. Illuminance levels 42 ft from the exterior wall peak at approximately 250 lux. Though this does not provide 100% of the ambient illuminance, it does reduce the electric lighting load significantly.

As anticipated, the north side of the building has a substantially different daylighting character. Interior illuminance for this diffuse-light-driven scheme does not reach the high levels of the south side, though there is a peak at 800 lux (due to the early morning burst of beam sunlight from its slightly north-east orientation). Except for this anomaly, the north-side illuminance curves are relatively level. All monitored positions show fairly constant levels of illuminance throughout the day. Again the center aisle position is below the 350-lux target but on the average provides the same level of illumination as that found on the south side. The sensors 13 ft from the atrium and 13 ft from the exterior wall show illuminance levels somewhat above the 350-lux target. By comparison, the generally higher illuminance levels of the south side indicate an overperforming daylighting system with potential energy penalties from excess HVAC cooling loads.

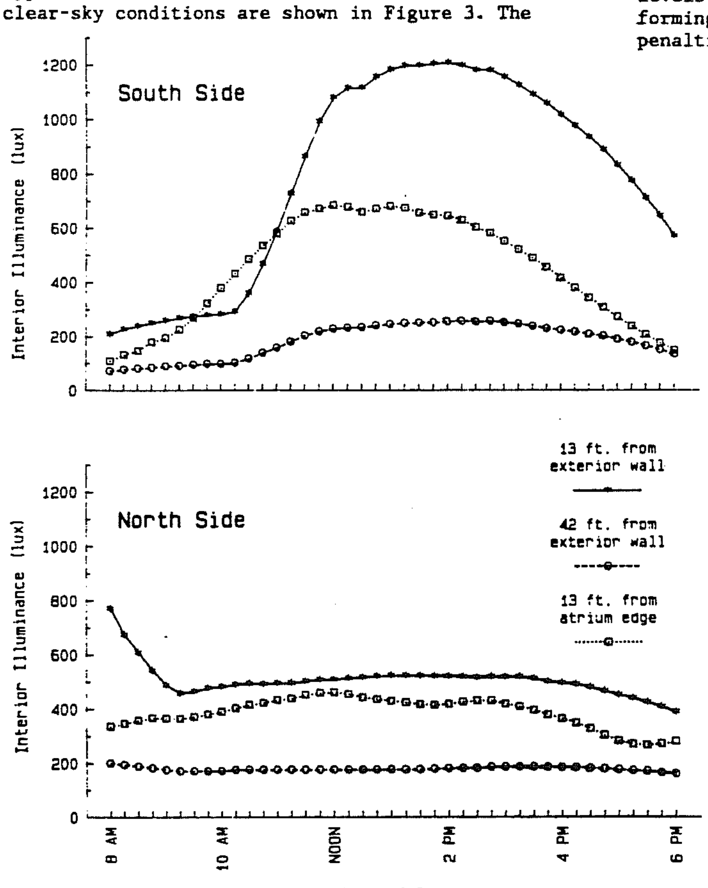
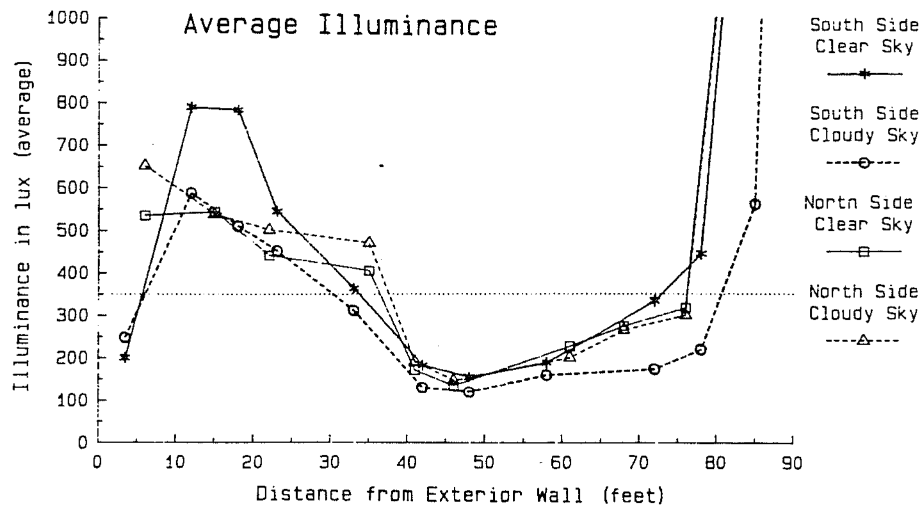


Figure 3. Interior illuminance on a horizontal plane 5'8" above the floor. Data represent the daylight component on a typical, clear summer day.

Figure 4 shows sectional illumination profiles across the north- and south-side sections on a clear sunny summer day. The sharp illumination gradients at the atrium edges are evident. Confirming the qualitative observations, this graph also clearly shows the drop in illuminance under the south-side light shelf, an area that never exceeds the 350-lux target illumination level.

6. ELECTRIC LIGHT DIMMING POTENTIAL

Data from these unoccupied summer days was used to evaluate the electric light dimming potential inherent in the building's available daylight. Illuminance readings for 24 locations across the north-south building section were collected at 15-minute intervals for normally occupied hours (8 A.M.-6 P.M.) and sorted into bins with 70-lux increments. The general patterns of this illuminance data are summarized in Figure 5. The number of occurrences in each bin was multiplied by the lighting power percentage required to raise that bin to the 350-lux target illumination level. Finally a summation of electric energy required by each monitored location was weighted by the cross-sectional area represented by that location. The results portray the supplemental electric power theoretically required to meet target illuminance levels of 350 lux. From these figures the electric light dimming potential can be determined.



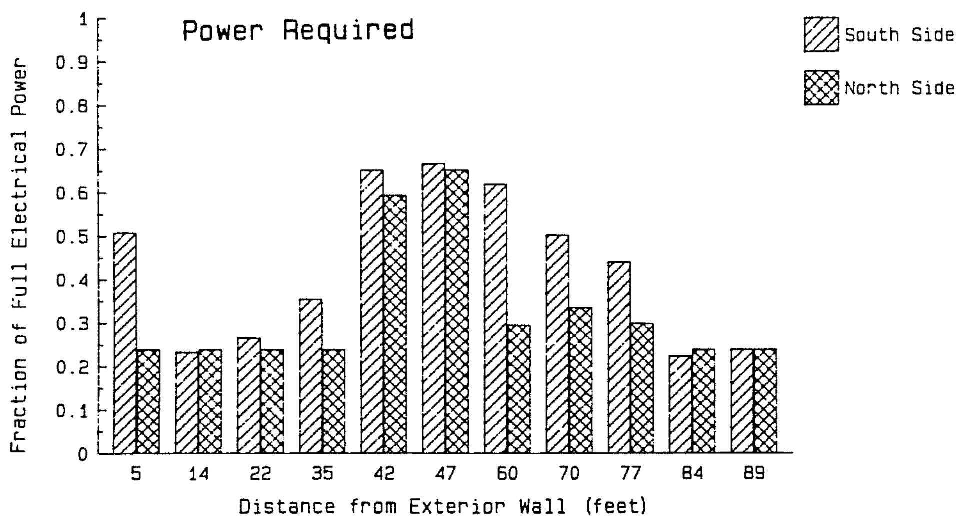


Figure 4. Average interior illuminance and lighting power theoretically required for typical summer conditions. The illuminance data represent daytime averages (8AM - 6PM) for the daylight component only. Power required to achieve the 350-lux target illuminance is based on calculations for the same period.

The binned illuminance data for the south-side exterior and atrium zones show some interesting trends. As might be expected, the south exterior zone with its relatively high light levels demonstrates considerable potential for dimming. The calculations indicate that for occupied hours during this summer period, the zone only requires 39% of the lighting potentially available from the indirect ambient lighting system. The area directly beneath the light shelf is responsible for about a quarter of the electric lighting requirement, as is the zone nearest the central corridor. One would intuitively expect the central corridor area (45 ft from the exterior wall) to require supplemental lighting; but ironically, the area below the light shelf, the zone with greatest access to daylight, requires continuous supplemental light.

The south-side atrium zone, receiving only diffuse daylight from the atrium, requires higher levels of supplemental electric light, 50% of full lighting power. When combined with the south exterior zone performance, this reflects an average electrical power requirement of 44% for the south side.

A similar analysis of the north side's dimming potential provides results that are counter-intuitive at first inspection. The north side of the building, without the strong beam illumination component of the south side, requires less supplemental electrical lighting. Although the north side lacks the high daylight levels found on the south side, it consistently has enough daylight to meet the 350-lux target level. Consequently the "darker" north side exhibits a higher potential for electric light dimming than the "brighter" south side. Our calculations indicate that the north exterior zone requires only 26% of the possible electric ambient lighting as a supplement to daylight. The north atrium zone also compares favorably with the south side in requiring only 35% of potential electric lighting. Only the center corridor area of the north side requires substantial electrical lighting. The north exterior and atrium zones combined require an average of 31% of full electrical power.

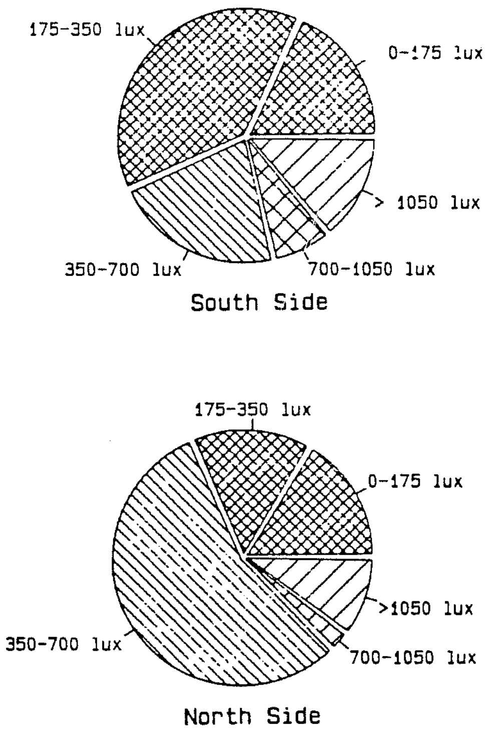


Figure 5. Distribution of interior illuminance levels over a typical unoccupied summer day.

The distribution of required electrical lighting power (as a fraction of full power) across both the north- and south-side building sections is summarized graphically in Figure 4. (Note that because of the electrical operating characteristics of the dimming system the ambient electric lights cannot be dimmed to below 24% of full power.) These calculations provide an impressive index of the electrical light savings that are made possible by the interior illumination delivered by the architectural features of the building. Based on our summer-period data, the average energy consumption figure for north-side and south-side zones combined is 37% of full power, reflecting 62% dimming of the electrical ambient illumination system.

7. CONCLUSIONS

This study has shown that the architectural daylighting features are performing well in providing for the ambient lighting needs of this building and can potentially produce significant reductions in electrical energy consumption. Based on the summer-period data reported here, potential energy reductions down to 37% of full power can be expected for the ambient lighting system. The actual measured savings are less than this. [1] However, relatively simple changes in the placement of the sensors for the electric light dimming system should improve the measured performance.

Although the north side doesn't have the dynamic lighting qualities of the south side, overall it out-performs the south in achieving the 350-lux target illumination level. The electric light dimming potential of the north side is only 31% of full power, compared to 44% for the south.

The more intense lighting levels of the south side do not provide additional benefit in the form of electric light dimming because they exceed the target level for ambient illuminance. There are perhaps savings from these high light levels in the displacement of task lighting in the south exterior zone, but once the 350-lux target level has been achieved, surplus light becomes more of a liability because of increased solar heat gain.

The combination of very-low-transmittance glazing (17%) and shading by the exterior light shelf makes the south exterior zone under the light shelf one of the dimmest areas in the building. Though it potentially has abundant access to daylight, it requires continuous supplemental light in the summer months.

The central atrium gives a dramatic flair to the space and offers a pleasant visual focus to this large-scale, open-plan office structure. At the same time the strong downward component of its daylight is less effective at providing light deep into adjacent interior spaces. The atrium edge is the location of a sharp gradient in natural light levels.

In this study, we focused on the quantitative aspects of daylighting analysis. The building's occupants are generally pleased with the overall lighting quality, but extensive post-occupancy surveys have not yet been performed.

The monitoring of daylighted buildings to evaluate the performance of their daylighting schemes provides significant insights into the complex interactions of the daylighting components and the dynamic nature of natural light. The information gained is sometimes counterintuitive and is an invaluable addition to our knowledge of the effective use of daylight in buildings.

8. ACKNOWLEDGMENTS

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